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THE GALACTIC CENTER HE I STARS: REMAINS OF A DISSOLVED YOUNG CLUSTER?

ORTWIN GERHARD
Astronomical Institute of the University of Basel, Venusstrasse 7, CH-4102 Binningen, Switzerland
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ABSTRACT

A massive young star cluster embedded in its parent molecular cloud will spiral into the Galactic Center from $\sim 30\,$pc during the life-time of its most massive stars, if the combined total mass is $\sim 10^6\,\mathrm{M}_\odot$. On its way inwards the system loses most of its mass to the strong tidal field, until the dense cluster core of high-mass stars is finally disrupted by the central black hole. A simple model is presented to argue that this scenario may under plausible conditions explain the observed location and rotation of the Galactic Center HeI stars. Accretion of star clusters into the Galactic Center could be recurrent, and play an important role in regulating the activity of Sgr A*.

1. INTRODUCTION

The central parsec of the Galaxy contains a cluster of young stars, including some 15 very luminous HeI emission line stars (Krabbe et al. 1995), as well as many less massive O and probably B stars (Eckart et al. 1999). From their spectroscopic properties and wind outflow velocities the HeI stars are believed to be evolved supergiant stars of $\sim 20 - 100\,\mathrm{M}_\odot$, now in a short-lived post-main sequence phase close to the Wolf-Rayet stage (Najarro et al. 1997). The most massive of these stars have a total age of $\lesssim 3\,$Myr, while the less luminous stars could have ages up to $\sim 8\,$Myr. Krabbe et al. (1995) have argued that the most likely origin of these stars is in a small starburst $\sim 3 - 7\,$Myr ago.

In situ formation of these stars is problematic, however, because of the strong tidal field of the nuclear bulge and central black hole. In this respect the Galaxy may differ from some other late type galaxies with observed young nuclear clusters (Carollo et al. 1998, Matthews et al. 1999, Böker et al. 1999). The tidal forces from the Galactic nucleus alone are sufficient to unbind gas clouds with densities $n_{\mathrm{crit}} < 10^7\,\mathrm{cm}^{-3}(1.6\,\mathrm{pc}/R_G)^{1.8}$ at galactocentric radii R_G (e.g., Morris 1993), while clouds in the nuclear gas disk have densities of $10^4 - 3\times10^5\,\mathrm{cm}^{-3}$ (Genzel 1989, Güsten 1989). Hence Morris (1993) has argued that the formation of the central star cluster must have been externally triggered to achieve the required high densities, e.g., by cloud collisions. An alternative model in which the massive stars form through collisions and mergers of lower mass stars in the high-density nuclear cluster now appears unlikely, both because too few massive stars would form (Lee 1994), and because similar stars have been found in the Arches and Quintuplet clusters some 30 pc away from the center (Serabyn et al. 1998, Figer et al. 1999a).

This letter explores the idea that the young stars now seen in the Galactic Center (GC) did not in fact form there, but further out in a massive star cluster that subsequently spiralled into the nucleus and tidally dissolved. One of the exciting results from HST has been the discovery of young star clusters in a variety of starburst environments (e.g., Whitmore & Schweizer 1995, O'Connell et al. 1995, Oestlin et al. 1998). The Arches and Quintuplet clusters at $\sim 30\,$pc distance from the GC testify that a similar star formation mode has been occurring in the nuclear disk of the Galaxy. Both clusters have ages of a few megayears and estimated total masses (extrapolating the IMF to $1\,\mathrm{M}_\odot$) of $\sim 10^4\,\mathrm{M}_\odot$ (Figer et al. 1999b). The orbits of such clusters will evolve by dynamical friction against field stars in sufficiently dense stellar systems (Tremaine, Ostriker & Spitzer 1975). Here I show that a massive cluster formed near the present location of the Arches cluster and embedded in the remains of its parent molecular cloud will indeed spiral into the central parsec within the lifetime of its most massive stars, losing much of its mass on its way inwards until its dense core is finally disrupted by the central black hole.

2. MASSIVE CLUSTER INFALL

Suppose a massive star cluster is formed at initial galactocentric radius $R_i = 30R_{30}\,$pc. The mass distribution of the nuclear bulge in $2\,\mathrm{pc} < R_G < 30\,\mathrm{pc}$ can be approximated as an isothermal sphere (Genzel, Hollenbach & Townes 1994, Fig. 7.1), with circular velocity $v_c = 130v_{130}\,\mathrm{km\,s}^{-1}$ in this range of radii, and

$$M_G(R_G) = 3.9\times10^6 v_{130}^2 R_G[\mathrm{pc}]\,\mathrm{M}_\odot. \qquad (1)$$

Eq. (1) implies that the mean density within $10 - 30\,$pc corresponds to $10^{5.5} - 10^{4.5}$ H-atoms per cm^3, so in this region molecular clouds with the densities observed in the GC may indeed collapse and form stars.

The newly formed cluster will lose orbital energy by dynamical friction against the nuclear bulge stars and spiral into the center on a time-scale

$$\tau_{\mathrm{df}} = \frac{1.17}{\ln(0.4N)}\frac{R_i^2 v_c}{Gm_c} = 3.1\times10^6 R_{30}^2 v_{130} m_6^{-1}\lambda_{10}^{-1}\,\mathrm{yr}, \quad (2)$$

where the cluster mass is $m_c = 10^6 m_6\,\mathrm{M}_\odot$ and the Coulomb logarithm $\lambda_{10} = \ln(0.4N)/10 > 1$ in the region of interest (Binney & Tremaine 1987). This simple equation suggests that a massive cluster, $m_c \sim 10^6\,\mathrm{M}_\odot$, when formed in the same region as the present Arches cluster, will indeed spiral into the center within the lifetime of its most massive stars.

The friction time-scale is dominated by the time spent at large radii. In these initial phases the cluster will be embedded within its parent molecular cloud while both are dragged inwards together. The time-scale for the cloud envelope of the cluster to be dispersed by the energy input from the massive cluster stars is comparable to the lifetimes of these stars, so will be a substantial fraction of the time to spiral into the GC. Because the part of the molecular cloud not converted into cluster stars is conceivably the major part of the total initial mass, we need to take into account the dynamical friction on the molecular cloud (Stark et al. 1991) when considering the orbital evolution of the cluster.

As it spirals to the Galactic center, the parent cloud and embedded cluster will constantly lose mass because of the strong tidal field. We can estimate the effect of this mass loss on the friction time with a simple model in which the initial mass m_{ci} of the combined cloud and cluster is distributed according to an isothermal profile, tidally limited at radius $r = r_{ti}$:

$$m_c(r) = m_{ci}(r/r_{ti}), \tag{3}$$

$$r_{ti} = \left(\frac{m_{ci}}{M_G[R_i]}\right)^{1/3} R_i = 6.2\, m_6^{1/3} v_{130}^{-2/3} R_{30}^{2/3}\,\mathrm{pc}. \tag{4}$$

For comparison, the half-mass radius of the present Arches cluster ($\sim 10^4\,\mathrm{M}_\odot$) is approximately $0.2\,\mathrm{pc}$ (Figer et al. 1999a). As the cluster spirals in, successive outer shells of the mass distribution are peeled off by the tidal field. The division between cluster and cloud need not be specified now, but it is clear that at some stage the cloud envelope will have been removed and the cluster proper will begin to be stripped. The tidal radius decreases according to

$$r_t/R_G = r_{ti}/R_i, \tag{5}$$

where R_G is the current galactocentric radius, and if internal evolution is neglected, the cluster mass decreases as

$$m_c(R_G) = m_{ci}(R_G/R_i). \tag{6}$$

When the entire cluster is finally disrupted at radius $R_{\rm dis}$, only a fraction $\sim R_{\rm dis}/R_i$ of the initial mass m_{ci} will have arrived at $R_{\rm dis}$. Note that assuming an isothermal profile for the cluster will lead us to overestimate its mass loss because real clusters have less extended envelopes than $\propto r^{-2}$, while neglecting internal evolution will lead us to underestimate the mass loss because the cluster will become less dense and more vulnerable to tidal disruption during the evolution.

We can now write a modified dynamical friction equation using the same arguments as in Binney & Tremaine (1987), and assuming that the instantaneous specific angular momentum loss due to the frictional force is the same for stripped material and material that remains bound to the cluster. This gives $R_G \mathrm{d}R_G/\mathrm{d}t = -0.428 G \ln(0.4N) v_c^{-1} m_{ci}(R_G/R_i)$, the solution of which is

$$\begin{aligned}\tau'_{\rm df}(R_i, R_G) &= R_i R_G v_c / 0.428\,\ln(0.4N)\, G m_{ci} \\ &= 6.2\times10^6 (R_G/R_i) R_{30}^2 v_{130} m_6^{-1} \lambda_{10}^{-1}\,\mathrm{yr}.\end{aligned} \tag{7}$$

Thus in this simple model the total time to spiral in from radius R_i is just twice that when the mass m_{ci} remains constant [eq. (2)], and the time taken from radius $R_G < R_i$ for a cluster that started out tidally limited at R_i is linearly proportional to R_G. Eq. (7) predicts that to reach the center in $\sim 3\times10^6\,\mathrm{yr}$ from $R_i \simeq 30\,\mathrm{pc}$, a mass-losing cloud-cluster system must have an initial mass $\sim 2\times10^6\,\mathrm{M}_\odot$, and $\sim 2\times10^5\,\mathrm{M}_\odot$ from $R_i \simeq 10\,\mathrm{pc}$. These are actually overestimates because we have neglected the frictional force from the previously stripped material and its polarization cloud that both lag behind the remaining bound cluster, as well as any additional drag from the nuclear gas disk.

3. FINAL TIDAL DISRUPTION AND THE HEI STAR CLUSTER

The preceding discussion shows that only the inner parts of the young star cluster will spiral into the Galactic center proper, while its outer parts and the cloud envelope will be left behind and distributed further out. There are good reasons to believe that the massive stars will be concentrated towards the cluster core. There is some evidence that high-mass stars form predominantly in or near the cores of young clusters (Fischer et al. 1998, Bonnell & Davies 1998). After star formation is complete, dynamical mass segregation will further accentuate the central concentration of massive stars, acting on their two-body relaxation time-scale. Thus the most massive cluster stars will almost all end up in the GC, as is required by the observed distribution of HeI stars.

Next we must ask whether the density of the cluster core is high enough to reach the central parsec. The GC HeI stars are observed at galactocentric radii $R_G = 1 - 10'' = 0.04 - 0.4\,\mathrm{pc}$ and their proper motions and radial velocities show a coherent rotation pattern (Genzel et al. 2000). In the present scenario this would be interpreted as tracing the last orbit of the cluster core before final disruption, giving a radius of disruption $R_{\rm dis} \lesssim 0.4\,\mathrm{pc}$. In this radial range the gravitational force of the central black hole dominates that of the nuclear bulge. We can thus estimate the mean density of the cluster core at $R_{\rm dis}$ as

$$\begin{aligned}\rho_{\rm dis} &= 3m_c(R_{\rm dis})/4\pi r_t^3(R_{\rm dis}) = 6M_\bullet/4\pi R_{\rm dis}^3 \\ &= 2.2\times10^7 M_3\,(R_{\rm dis}/0.4\,\mathrm{pc})^{-3}\ \mathrm{M}_\odot\,\mathrm{pc}^{-3},\end{aligned} \tag{8}$$

where we have written the black hole mass as $M_\bullet = 3\times10^6 M_3\,\mathrm{M}_\odot$ (Genzel et al. 2000). Notice the sensitivity to the disruption radius.

The observed average stellar density in the Arches cluster, extrapolated to include stars down to $1\,\mathrm{M}_\odot$, is $6.3\times10^5\,\mathrm{M}_\odot/\,\mathrm{pc}^3$ (Figer et al. 1999a). Evolutionary calculations by Kim et al. (1999) show that dynamical evolution and rapid mass segregation lead to the formation of a core of high mass stars with density reaching $\rho_c \simeq 10^7\,\mathrm{M}_\odot/\,\mathrm{pc}^3$ in the mild core collapse stage, after $\sim 1\,\mathrm{Myr}$ evolution in their $2\times10^4\,\mathrm{M}_\odot$ cluster models. A central density of $\sim 10^7\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$ in the core of the disrupting cluster thus appears reasonable, but significantly larger densities (required for smaller $R_{\rm dis}$) would seem problematic.

The required high cluster core density is most easily maintained in a phase after core collapse when the energy loss of the core from evaporation is compensated by the energy gain from three-body binaries. This requires the core to be dominated by the 100 most massive stars (Binney & Tremaine 1987), previously concentrated into this volume by mass segregation. The high-density phase will last longer for more massive clusters, arguing for larger initial masses for the disrupting cluster than for the Arches cluster.

After the cluster core begins to disintegrate, it continues to spiral inwards until torques from the polarization cloud and the material lost previously become ineffective, that is, until the debris has spread in angle by $\Delta\phi \sim \pi$.

The time for the debris within αr_t of the cluster center to spread by $\Delta\phi = \pi$ is

$$t_{\rm spr} \equiv \frac{\pi}{\left|\frac{{\rm d}\Omega}{{\rm d}R_G}\right|_{R_{\rm dis}} 2\,\alpha\, r_t(R_{\rm dis})} = \frac{t_{\rm rot}}{6}\,\frac{R_{\rm dis}}{\alpha\, r_t(R_{\rm dis})}, \qquad (9)$$

which gives of order $t_{\rm rot}/\alpha$ according to eqs. (4), (5). The rotation period near the black hole is $t_{\rm rot} = 13700 M_3^{-1/2} (R_G/0.4\,{\rm pc})^{3/2}\,{\rm yr}$, so for the cluster center $t_{\rm rot}/\alpha$ can be several 10^4 yr. For comparison, the dynamical friction time (2) for $10^4\,{\rm M}_\odot$ to spiral from $R_{\rm dis} = 0.4$ pc into the center completely is only 50000 yr. This suggests that the debris of the cluster core will spiral inwards significantly even after the final disruption, and that therefore the rotation pattern observed down to $R_G \simeq 0.15$ pc is consistent with disruption at radii ~ 0.4 pc. It will be interesting to simulate this disruption event in the black hole's tidal field with N-body models.

4. DISCUSSION

In summary, the previous sections have shown that under plausible conditions a young star cluster formed in the Galactic nuclear disk may spiral into the GC within the life-time of its most massive stars, and that the density in its core of high-mass stars can be such that it would actually reach and dissolve in the region where the GC HeI stars are observed. This requires either that the cluster itself is substantially more massive than the Arches and Quintuplet clusters, or that it forms within a massive molecular cloud (such as the present Sgr clouds) whose large mass dominates the frictional force initially (see also Stark et al. 1991), or a combination of both.

A further condition is that the cluster must not evaporate in the strong tidal field of the nuclear bulge before it reaches the center. In typical models for the Arches and Quintuplet clusters ($m_c = 2\times10^4\,{\rm M}_\odot$) by Kim et al. (1999) the evaporation time is found to be several Myr. Evaporation occurs on a time-scale proportional to the half-mass relaxation time (Spitzer & Hart 1971)

$$t_{rh} = 2.0\times10^8\, m_6^{1/2}\, r_1^{3/2}\, m_{*,\odot}^{-1}\, \lambda_{10}^{-1}\ {\rm yr}, \qquad (10)$$

where $r_h = r_1$ pc is the cluster half-mass radius and $m_* = m_{*,\odot}\,{\rm M}_\odot$ the average stellar mass, but depends also strongly on the strength of the tidal field. t_{rh} is rather sensitive to the uncertain half-mass radius. For the Arches cluster Figer et al. (1999a) found $r_h = 0.2$ pc from the observed high-mass stars, i.e., without correction for initial or dynamical mass segregation. We can rewrite $t_{rh} \propto m_c^{1/2} r_h^{3/2} \propto m_c \rho^{-1/2}$ and consider the mean density to be fixed by the external tidal field. This suggests that the most massive clusters will have the longest evaporation times, and therefore again that they are the most likely to reach the central parsec within 3 Myr, even though evaporation depends on several other parameters.

A prediction of the present model for the origin of the GC HeI stars is that the massive stars in the core of the disrupting young cluster should end up at smaller galactocentric radii than lower mass stars in the cluster envelope. Krabbe et al. (1995) estimate the total stellar mass corresponding to the nuclear HeI star cluster from various observed quantities, assuming a mass function $\propto m^{-2}$ down to $m_* = 1\,{\rm M}_\odot$, as $\sim 1.5\times10^4\,{\rm M}_\odot$. The number of low-mass stars associated with the cluster is unknown, but a standard Salpeter IMF with the same number of the highest mass stars, extrapolated to $m_* = 1\,{\rm M}_\odot$, gives $\sim 10^5\,{\rm M}_\odot$. Most of these stars should now be found at galactocentric radii of a few parsec (some tens of arcsec) or further out if the cluster was even more massive. Could these stars be related to the young population seen by Philipp et al. (1999), or was the formation of the cluster just part of a larger-scale starburst?

Another issue to be addressed is the observed counterrotation of the HeI stars with respect to Galactic rotation (Genzel et al. 2000). As in alternative models, counterrotation is not inherent in the present scenario. However, a large molecular cloud entering the nuclear disk with orbital angular momentum roughly antialigned with Galactic rotation would sooner or later suffer a strong collision, and this in fact might be the event triggering the formation of the cluster. The subsequent dynamical friction on the cluster and its surrounding cloud envelope would then act to circularize the counterrotating orbit while the cluster spirals in, explaining the rotating torus structure of the HeI stars observed now. This observation would be much more difficult to explain in models where the GC young stars form in a cloud collision near their present location, because these stars should then still reflect some of the cloud's initial orbital motion.

How common could cluster accretion events be in the GC? Observationally, the presence of $\sim 10^8$ yr old AGB stars in the central parsec (Krabbe et al. 1995) suggest that it has happened before at least once, and perhaps one of the massive molecular clouds in the vicinity is the next candidate. Clearly, a constant cluster accretion rate, $\sim 10^5\,{\rm M}_\odot$ per 3×10^6 yr if the present configuration were typical, would build up substantial mass in the nuclear bulge over time. The total mass inflow rate of $\sim 0.1\,{\rm M}_\odot/\,{\rm yr}$ inferred from dynamical friction on the GC giant molecular clouds on x_2-orbits at ~ 100 pc (Stark et al. 1991), and somewhat more from gas flow through the ILR at ~ 200 pc (Gerhard 1992, Serabyn & Morris 1996) would supply sufficient gaseous material to maintain this rate of cluster formation in addition to other distributed star formation. Detailed observations of the young stellar population in the GC are needed to see whether the process actually happens recurrently and whether it is a substantial factor in building up the nuclear bulge. Early-on, clusters would spiral in as far as there are field stars to provide the background for dynamical friction. Later clusters would come in further and build up a density gradient (assuming the angular momentum can be further transported outwards). In the simple model described in Section 2, where both the nuclear bulge and cluster density profiles are $\propto r^{-2}$, the ingoing cluster's tidally stripped material would also be distributed $\propto r^{-2}$.

Independent of the rate of cluster accretion, the recent arrival in the GC of a cluster with a large number of massive stars would have profoundly changed the physical conditions in the central parsec and may in fact be responsible for the present lack of activity of Sgr A*. If so, stellar population studies of the frequency of cluster accretion in the GC will have some general impact on understanding the nuclear activity cycles in spiral galaxies.

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REFERENCES

Binney, J., & Tremaine, S. 1987, Galactic Dynamics, Princeton Univ. Press, Princeton
Böker, T., van der Marel, R.P., & Vacca W.D. 1999, AJ, 118, 831
Bonnell, I.A., & Davies, M.B. 1998, MNRAS, 295, 691
Carollo, C.M., Stiavelli, M., & Mack, J. 1998, AJ, 116, 68
Eckart, A., Ott, T., & Genzel, R. 1999, A&A, 352, L22
Figer, D.F., McLean, I.S., & Morris, M. 1999a, ApJ, 514, 202
Figer, D.F., Kim, S.S., Morris, M., Serabyn, E., Rich, M.R., & McLean, I.S. 1999b, ApJ, 525, 750
Fischer, P., Pryor, C., Murray, S., Mateo, M., & Richtler, T. 1998, AJ, 115, 592
Genzel, R. 1989, in IAU Symp. 136, The Center of the Galaxy, ed. M. Morris, (Dordrecht, Kluwer), 393
Genzel, R., Hollenbach, D., & Townes, C.H. 1994, RepProgPhys, 57, 417
Genzel, R., Pichon, C., Eckart, A., Gerhard, O.E., & Ott, T. 2000, MNRAS, in press
Gerhard, O.E. 1992, RevModAstron, 5, 174
Güsten, R. 1989, in IAU Symp. 136, The Center of the Galaxy, ed. M. Morris, (Dordrecht, Kluwer), 89
Kim, S.S., Morris, M., & Lee, H.M. 1999, ApJ, 525, 228
Krabbe, A., et al. 1995, ApJ, 447, L95
Lee, H.M. 1994, in The Nuclei of Normal Galaxies, ed. R. Genzel, A.I. Harris, 335
Matthews, L.D., et al. 1999, AJ, 118, 208
Morris, M. 1993, ApJ, 408, 496
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R.P., & Hillier, D.J. 1997, A&A, 325, 700
O'Connell, R.W., Gallagher, J.S., Hunter, D.A., & Colley, W.N. 1995, ApJ, 446, L1
Oestlin, G., Bergvall, N., & Roennback, J. 1998, A&A, 335, 850
Philipp, S., Zylka, R., Mezger, P.M., Duschl, W.J., Herbst, T., & Tuffs, R.J. 1999, A&A, 348, 768
Serabyn, E., Shupe, D., & Figer, D.F. 1998, Nature, 394, 448
Spitzer, L., & Hart, M.H. 1971, ApJ, 164, 399
Stark, A.A., Gerhard, O.E., Binney, J.J., & Bally, J. 1991, MNRAS, 248, 14P
Tremaine, S., Ostriker, J.P., & Spitzer, L. 1975, ApJ, 196, 407
Whitmore, B.C., & Schweizer, F. 1995, AJ, 109, 960